Estimation of Snowmelt Runoff in Beas Basin, India

Vajja Hari Prasad
Water Resources Division, Indian Institute of Remote Sensing,
P.B., No. 135, 4, Kalidas Road, Dehradun - 248 001
Uttranchal, India
E-mail: prasad@iirs.gov.in, v_h_p@indiatimes.com

Partha Sarathi Roy
National Remote Sensing Agency, Balanagar
Hyderabad-500037, India
E-mail: dda@nrsa.gov.in, roy-pse@hotmail.com

Abstract

Estimation of snowmelt runoff is very important in the Western Himalayan rivers in India where it is required to plan for hydropower generation and the water management during the non-monsoon season. An attempt has been made to estimate snowmelt runoff on a 10 day average basis in Beas Basin up to Pandoh Dam during May, 1998 and November, 1999 using a Snowmelt Runoff Model (SRM), which is a degree day method. The input parameters for the model are derived from existing maps, satellite data, metrological and hydrological data. The relief of the basin is divided into 12 elevation zones of 500 m each. The temperature was extrapolated to these elevation zones using temperature lapse rate calculated using the observed temperature at seven stations within the basin. Snow covered area in the basin was determined using Indian Remote Sensing Satellites IRS - 1C / 1D Wide Field Sensor (WIFS). The runoff from the snow covered area and snow free area was separately calculated in each elevation zone. The model parameter degree-day factor is taken from literature and runoff coefficients for snow and rain are derived using the observed data. The total discharge at the dam site is computed by a weighted sum of runoff components from all the elevation zones. There is a good agreement between the observed and computed runoff with a coefficient of determination of 0.854 and the difference in volume is + 4.6 %.

Introduction

The Himalayas are the largest mountain range in the world, extending over a length of 2500 km. They are the storehouse of fresh water for the Indus, Ganga and Brahmaputra rivers. Snowmelt runoff varies from west to east and is important in the Western Himalayas as Ganga river originates here. The proportion of the annual stream flow generated from snowmelt in the Himalayas is about 30-50 % of the major rivers (Aggarwal, 1983). Snowmelt runoff is important as it starts in the spring (March to May) when water is needed most, particularly if the monsoon in the previous years has failed. Despite the importance of snowmelt water contribution to the hydrology of the Himalayan Rivers, its characteristics are less understood primarily due to the complexities of the processes involved in snow hydrology and the lack of hydro-meteorological data in the high altitude areas. The unique combination of intense seasonal precipitation and steep topography makes the hydrology in the region very complex. The seasonal snowline descends to an altitude of 2000 m in the western part of the Himalayas by February. As the snowmelt commences in March, the snow line starts receding upwards and by the end of June to an altitude of 4500 m. Snowmelt studies in India have not been carried out in detail in spite of their prime importance for the management of the water resources. Only some efforts have been made to develop regression relationships between the snow cover area (SCA) and runoff (Ramamoorthi, 1986).

Accurate estimation of the volume of water stored in the snow pack and its rate of release is essential to predict the flow during the snowmelt period. For an estimation of the snowmelt, the information on snow cover depth and water equivalent is a pre-requisite. In the mountainous watersheds, very little information relating to meteorological and physical factors affecting runoff is available. Snowmelt is not measured quantitatively but must be estimated.

The factors involved in the computation of snowmelt are so numerous that it is practically impossible to account for all of them. Some of them are not regularly measured or are available only on experimental sites. An important variable in the mountainous watersheds during the snowmelt season is the aerial extent of the snow cover. It determines the part of the watershed, which contributes to the snowmelt runoff. Periodical monitoring of the SCA during the snowmelt season is an essential requirement for short-term forecasts of the daily river flows and for seasonal forecasts of runoff volume.

Measurement of snow cover in the mountainous basins is very difficult. Conventional methods have limitations in the monitoring of snow-covered area in the Himalayan basins because of inaccessibility. Because of the difficulty of making field measurements in snow covered mountainous regions, remote sensing is perhaps the only means of measuring snow cover extent and properties. Remote sensing data can be used to obtain information about ice and snow in the visible, Near Infra Red (NIR), Thermal Infra Red (TIR), microwave wavelengths and geographic information system (GIS) can used to store, process and analyse the spatial data and their attributes. In terms of snowmelt runoff estimation, SCA and temperature are important parameters of estimation and can be obtained from remote sensing data and meteorological data. The generation of different elevation zones and a variety of thematic maps such as drainage, contours and their spatial and non-spatial analysis can be carried out through GIS techniques. Visual analysis of remote sensing is generally used to delineate the SCA.

Objectives of the study

In the present study the Snowmelt Runoff Model (SRM, Martinec, 1986) is used with ground information and meteorological data. The Beas Basin up to Pandoh Dam is selected for carrying out the study and the degree-day approach was adopted for snowmelt runoff estimation.
The main objectives of the study are as follows:

- Deriving the parameters required for the Snowmelt Runoff Model, using the geo-spatial database derived using satellite, topographic and meteorological data.
- Computation of runoff using Snowmelt Runoff Model.
- Comparison of the observed and computed runoff.

Review of literature

Martinec (1975) developed a snowmelt runoff model in small European basins. Rango (1983) applied remotely sensed snow cover data in snowmelt runoff modelling and Dozier (1984) demonstrated that LANDSAT 5 band 5 (1.57-1.78 um) is useful in discriminating between clouds and snow. Griggs (1968) has shown that melting snow has an emissivity as high as 99% and non-snow area has emissivity less than or equal to 95%.

Singh and Quick (1993) carried out stream flow simulation for the Satluj River in the western Himalayan region using the University of British Columbia (UBC) watershed model. The results indicated that combining two hydrologically different watersheds into a single watershed reduces simulation or forecasting accuracy. It was also concluded that spatial distribution of precipitation is the most important factor in stream flow simulation because the model from precipitation- elevation relationships builds up snow pack.

Singh, *et al*., (1997) estimated the average contribution of snow and glacier melt to the annual flow of the Chenab river at Akhnoor over a 10 year period using a water balance approach. Variability of the snow-covered area was also studied for the same period. It was concluded that 70.2% of the total drainage area was covered by snow during March/April and 24.3% remains covered by perpetual snow and glacier in September/October. The contribution of snow and glacier melt was 49.10%.

Singh, *et al*., (2000) determined the degree-day factor of snow and ice at an altitude of about 4000m over Dokrani Glacier in the Garhwal Himalayas region. The influence of a natural fine dust layer of 2mm thickness was also studied on snow and ice degree-day factors. The average degree-day factor for clean snow and dusted snow was computed to be 5.7 and 6.4 mm/ºC/day respectively, whereas for clean ice and dusted ice this factor was found to be 7.4 and 8.4 mm/ºC/day respectively. The presence of dust on the ice increased the degree-day factor by about 9%, whereas for snow it increased by about 12%, which indicated that the effect of dust on degree-day factor for snow was more pronounced than that for ice. The study confirmed that the average daily temperature computed as the mean of maximum and minimum temperatures is an equally good approach in both snowmelt and glacier melt runoff calculations when hourly data are not available.

Singh, *et al*., (2000) studied the storage characteristics of the Dokrani glacier and the influence of changes in the storage capacity on the hydrologic response of the basin. It showed that nighttime flow is as high as daytime flow throughout the melt season. In the beginning of the melt season, the night time flow is almost equal to daytime flow, but in the later part of the melt season, night time flow is slightly lower than the day time flow. The reduction in snow pack area and depths resulting in exposition of larger extent of glacier ice surface and development of drainage network with melt season were understood to be the main factors attributing to reduction in storage capacity with advancement of melt season. It was observed that the hydrologic response of the basin becomes faster with time during the melt season. The results also indicated that the delaying influence of the glacierised basin reduces with time due to changes in physical condition of the basin and results in a quicker response of melt water to stream flow in mid or late melt season.

Kumar, et.al., (1993) studied in the Beas basin up to Thalot gauging site with a drainage area of 5144 km^2. The basin was divided into 6 elevation zones and snow cover area was derived using the LANDSAT Multi Spectral Scanner (MSS) sensor data. The finding of this study is a relative seasonal difference of 18.1 % and a goodness of fit of 0.78 between observed and computed snow melt runoff.

Physics of snowmelt: The physics of melting of snow and transformation of melt water into runoff are very important aspect of snow hydrology. Snowmelt is the overall result of different heat transfer processes to the snow pack. The sun is the ultimate source of energy responsible for the melting of the snow pack. There is a complex interaction between the incoming solar radiation, earth’s atmosphere and terrain surface. Hence a number of intermediate steps in the process of energy transfer to the snow surface have to be considered to understand the process of snowmelt and also to make quantitative estimations of the melt (Singh and Singh, 2001). The principal fluxes of heat involved are:

- Absorbed solar radiation,
- Interchange of long wave radiation between the snowpack and the atmosphere and surrounding features,
- Convective heat transfer to the air,
- Latent heat of vaporization released by the vapor condensed from the snow surface,
- Conduction of heat from the ground from the snow pack,
- Heat transferred from the snow pack.

Methods of snowmelt computation

There are two basic approaches generally adopted for estimation of snowmelt from a snow pack. The first approach is known as Energy Budget or Energy Balance Approach and the second is the Temperature Index of Degree-Day Approach.

Energy Budget or Energy Balance Approach: The energy balance or heat budget of a snow pack governs the production of melt water. This method involves accounting of the incoming energy, outgoing energy, and the change in energy storage for a snow pack for a given period of time. The net energy is then expressed as equivalent of snowmelt. The seasonal variability in the energy inputs available for melt in general increases towards the poles. The energy balance (Singh and Singh, 2001) of the snow pack for any time interval can be expressed as

$$Q_m = Q_{nr} + Q_h + Q_e + Q_p + Q_g + Q_q$$

Where,

Q_m = Energy available for melting of snowpack
Q_{nr} = Net radiation
Q_h = Sensible or convective heat from the air
Q_e = Latent heat evaporation, condensation or sublimation
Q_p = Heat content of rainwater
Q_g = Heat gained through conduction from underground
Q_q = Change of internal energy of the snowpack

The positive value of Q_m will result in the melting of snow. But because of the numerous and specific required data to use the energy balance method and their non-availability for this study, the Degree-Day method was chosen.

Degree-Day method

In the Himalayan Mountains, the meteorological network for data collection is very poor. The most generally available data are daily maximum and minimum temperatures, humidity measurements and surface wind speed. Temperature indices are widely used in the snowmelt estimation because it is generally considered to be the best index of the heat transfer processes associated with snowmelt. Air temperature expressed in Degree-Day is used in snowmelt computations as an index of the complex energy balance leading to snowmelt.

A degree-day is a unit expressing the amount of heat in terms of persistence of a temperature for 24-hour period of one degree centigrade departure from a reference temperature. The simplest and the most common expression relating daily snowmelt to the temperature index is,

$$M = D_f\ (T_i - T_b)$$

Where,

M = Melt produced in cm of water in a unit of time
D_f = Degree-day factor (cm ºC^{-1} day^{-1})
T_i = Index air temperature (ºC)
T_b = Base temperature (usually 0ºC)

Mean daily temperature is the most commonly used index of air temperature for snowmelt.

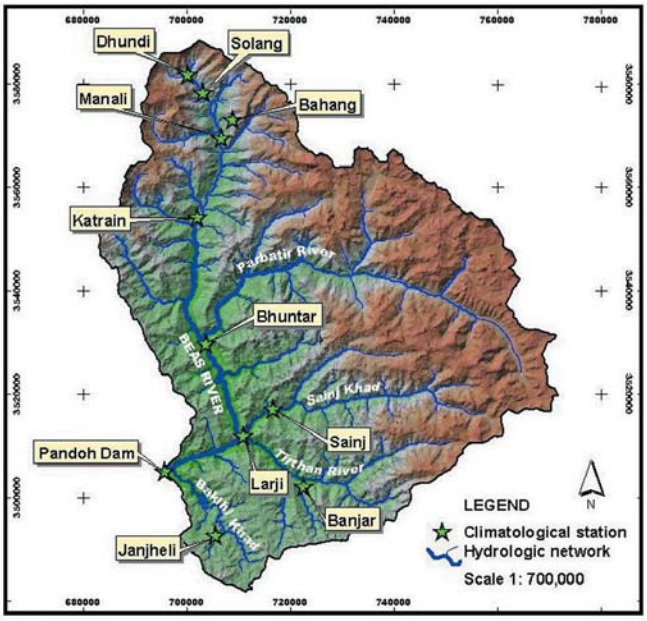

Figure 1 Drainage network of Beas basin (up to Pandoh dam) with location of hydro-meteorological station.

Snowmelt Runoff Model (SRM): The Snowmelt-Runoff Model (SRM: also referred to in the literature as the "Martinec Model" or "Martinec-Rango Model") is designed to simulate and forecast daily stream flow in mountain basins where snowmelt is a major runoff factor. SRM was developed by Martinec (1975) in small European basins. Thanks to the progress of satellite remote sensing of snow cover, SRM has been applied to larger basins. SRM can be applied in mountain basins of almost any size (so far it has been used from 0.76 to 122 000 km^2) and any elevation range (WMO, 1986). A model run starts with a known or estimated discharge value and can proceed for an unlimited number of days, as long as the input variables - temperature, precipitation and snow covered area - are provided. In addition to the input variables, the area-elevation curve of the basin is required. If other basin characteristics are available (forested area, soil conditions, antecedent precipitation, and runoff data), they are of course useful for facilitating the determination of the model parameters. SRM can be used for the following purposes:

- Simulation of daily flows in a snowmelt season, in a year, or in a sequence of years. The results can be compared with the measured runoff to assess the performance of the model and to verify the values of the model parameters.

Simulations can also serve to evaluate runoff patterns in ungauged basins and in a hypothetically changed climate.

- Short term and seasonal runoff forecasts.

Model structure: Each day, the water produced from snowmelt and rainfall is computed, by the using the equation (Martincec, et.al., 1998);

$$Q_{n+1} = [C_{Sn}\, a_n (T_n + \Delta T_n) S_n + c_{Rn} P_n] * A*(10000/86400) * (1-k_{n+1}) + Q_n k_{n+1}$$

where:

Q = average daily discharge (m^3s^{-1})

C = runoff coefficient expressing the losses as a ratio (runoff / precipitation), with c_S referring to snowmelt and c_R to rain

A = degree-day factor [$cm \cdot {}^oC^{-1} \cdot d^{-1}$] indicating the snowmelt depth resulting from 1 degree-day

T = number of degree-days [$^oC \cdot d$]

ΔT = The adjustment by temperature lapse rate when extrapolating the temperature from the station to the average hypsometric elevation of the basin or zone [$^oC \cdot d$]

S = Ratio of the snow covered area to the total area

P = Precipitation contributing to runoff [cm]. A pre selected threshold temperature, T_{CRIT}, determines whether this contribution is rainfall and immediate. If precipitation is determined by T_{CRIT} to be new snow, it is kept on storage over the hitherto snow free area until melting conditions occur.

A = area of the basin or zone [km^2]

k = recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall:

$= \frac{Q_{n+1}}{Q_n}$ (n, n+1 are the sequence of days during a true recession flow period).

n = sequence of days during the discharge computation period

$\frac{10000}{86400}$ = Conversion from $cm \cdot km^2 \cdot d^{-1}$ to m^3s^{-1}

In the present study since data were available as temporal average on 10 days, the model is modified and used to compute average snowmelt runoff over 10 day increments.

Study Area

The Beas basin up to Pandoh Dam is chosen for the study based on the availability of satellite data and meteorological data. The Beas River is an important river of the Indus River system. It takes off from the Rothang Pass at an elevation of 3900m and flows nearly north-south direction up to Larji. At Larji it takes a right angle and turns towards the southwest and flows in the same direction up to Pandoh Dam. The length of the Beas River up to Pandoh is 116 km, among its tributaries Parbati and Sainj Khad Rivers are glacier fed. The Beas River catchment up to Pandoh dam is 5406 km^2 out of which only 538 km^2 (from satellite image of October 1998) is under permanent snow (figure 1). The catchment area is largely comprised of precipitous slopes and the rocks are mainly bare. There are high peaks in the east as well as in the north of the river valley. The altitude varies from 802 m near Pandoh Dam up to 6600 m on the northeast border of the Parbati sub-catchment. A considerable portion of the river becomes snow covered during winter. During the summer, the Beas River is mainly fed by snowmelt. Some of the major tributaries which join upstream of Pandoh dam are: Parbati River near Bhuntar, Tirthan and Sainj Rivers near Larji, Sabari Nala near Kulu and Bakhli khad bear Pandoh Dam. Pandoh Dam is primarily a dam to divert water from the Beas River to Satluj River for power generation at Dehar Power House located on the right bank of River Satluj.

Data Used

Remote sensing data, hydro-meteorological data and other data have been used. More details of the data used are given here. The snow cover area in the Beas basin during May 1998 - November 1999 was determined using Indian Remote Sensing (IRS) satellite 1C/1D Wide Field Sensor (WIFS) satellite data. The WIFS sensor has 2 bands one each in visible (0.62 - 0.68 μm) and near infrared band (0.77 - 0.86 μm) of electro-magnetic spectrum. This sensor has a coarse spatial resolution of 188 m, which is adequate for large catchments. Hydro-meteorological data at a temporal frequency of ten daily (average) / daily rainfall data, ten daily (average) / daily temperature, ten daily (average) discharge were obtained from various sources such as Bhakra Beas Management Board (BBMB), Pandoh, Indian Agriculture Research Institute (IARI) research station, Katrain and Snow and Avalanche Studies Establishment (SASE), Manali.

Ten daily (average) / daily precipitation data were available at 10 rain gauge stations namely Pandoh, Banjar, Bhuntar, Katrain, Sainj, Janjheli, Manali, Solang, Dhundi, Bahang. Ten daily average / daily maximum and minimum temperature were available for 7 stations Pandoh, Bunthar, Larji, Katrain, Manali, Balang, Dhundi. Discharge is measured in various tributaries of Beas River, however in the present study the ten daily average discharge at the basin outlet i.e. Pandoh dam is used in the present study. The location of the meteorological stations and the drainage network is shown in figure 1. Other data used in the study are basin boundary and digital elevation model.

SRM Model Parameters

Model parameters were derived from basin characteristics, meteorological characteristics and other information.

Basin characteristics: The basin characteristics derived are elevation zones, area - elevation curve. Using the available digital elevation model, the relief of Beas basin is divided into 12 elevation bands or zones, of 500 m each. Using these elevation bands / zones, the mean elevation of each elevation zone is calculated, which is used to extrapolate the base station temperatures to different elevations and to calculate the degree-day factor(s) in each elevation zone. The meteorological factors derived are distribution of rainfall by Thiessen polygon, temperature distribution within each elevation zones and degree-day factor. There are 10 meteorological stations where rainfall / snowfall data are being recorded. Among these, 7 stations are recording only rainfall and 3 stations are recording rainfall / snowfall. As rainfall / snowfall measurement is a point measurement, it is converted to spatial data using the Thiessen polygon method. Using Thiessen polygon and the elevation zones, weighted rainfall in each elevation zone is calculated for the SRM model.

Temperature distribution: As the SRM model is a degree-day method; temperature is an important parameter spatially as well as temporally. The temperature data are being recorded in 7 stations with elevation varying from 837 m to 3050 m. Using these data, the lapse rate i.e. relation between temperature and elevation is calculated. During the years 1998 and 1999, the lapse rate was found to be 0.65ºC and 0.69ºC per 100m. Using this lapse rate the temperature at mean elevation of each elevation zone is calculated using temperature from the nearest station where it was measured. Critical temperature is assumed as 0ºC in this study, to know whether precipitation is rain or snow fall in each elevation zone. The degree-day factor converts the snow cover to snow melt expressed in depth of water. Degree-day factor is influenced by the physical properties of snow pack and because these properties change with time, this factor also changes. This study was carried out during the May 1998 to November 1999. During the year 1998, the snow accumulation season is from November onwards, during which only fresh snow will be there, hence the degree day factor used is 5.5 mmºC-1 day^{-1} and snow accumulation continues up to April and when actual snowmelt occurs snow will be dusted, hence the degree day factor of 6.0 mmºC^{-1} day^{-1}. These values are very close to the actual observed degree-day factors (Singh and Kumar, 1996) in Western Himalayas.

Snow covered area: This is dynamic parameter was derived using IRS-1C / 1D WIFS sensor during May 1998 to November 1999, with one satellite image for each month. However, for several months during monsoon (July - September, 1998) and March, April and August, 1999 satellite data was not available due to cloud cover. Using these satellite data, the snow line is delineated by visual interpretation and the percentage of snow cover area in each of the elevation zones is calculated and used in the model. During the months where satellite data was not available, the percentage of snow cover area is interpolated linearly from the available nearest month in each elevation zone. The monthly snow cover percentages in each elevation zone are given in table 1.

Runoff coefficient of rain: This indicates the percentage of rainfall converted to runoff. This has been calibrated based on the observed runoff on a monthly basis.

Runoff coefficient of snow: This indicates the percentage of snowfall converted to runoff. This has been calibrated based on the observed runoff on a monthly data.

Recession coefficient: Recession coefficient indicates the fraction of the discharge contribution from previous day's snowmelt on a given day. In this study, the observed 10 daily average discharges are plotted on log-log scale and the recession coefficient is determined on a 10 daily basis, which is the slope of the best-fit line. The coefficient of rain and snow and recession coefficient used in this study are given in table 2.

Table 2 Coefficient of Rain (Cr), Snow (Cs) and Recession (k).

Month	Cr	Cs	k
May	0.23	0.20	0.98
Jun	0.67	0.65	0.99
Jul	0.32	0.17	0.96
Aug	0.36	0.27	0.84
Sep	0.30	0.27	0.78
Oct	0.28	0.20	0.78
Nov	0.04	0.17	0.68
Dec	0.05	0.54	0.75
Jan	0.17	0.60	1.00
Feb	0.18	0.17	1.00
Mar	0.12	0.58	0.99
Apr	0.24	0.60	0.98
May	0.33	0.64	0.98
Jun	0.84	0.68	0.97
Jul	0.75	0.60	0.96
Aug	0.15	0.05	0.97
Sep	0.02	0.06	0.98
Oct	0.04	0.17	0.99

Table 1 Snow Cover Area (percentage) in Elevation Zones.

Monthly SCA per Elevation Zone in May, 98 to Nov,99 (%)								
Elev. Zone	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
MAY 98	0.7	23.4	78.9	97.3	99.9	100.0	100.0	100.0
JUN	0.2	2.5	33.5	83.9	97.8	99.9	100.0	100.0
JUL	0.1	1.9	25.3	67.5	94.8	99.9	100.0	100.0
AUG	0.1	1.2	17.0	51.1	91.8	99.8	100.0	100.0
SEP	0.0	0.6	8.8	34.7	88.9	99.7	100.0	100.0
OCT	0.0	0.0	0.6	18.3	85.9	99.6	100.0	100.0
NOV	0.0	0.0	12.1	69.4	97.3	99.9	100.0	100.0
DEC 98	0.0	0.4	19.9	72.1	97.5	99.9	100.0	100.0
JAN 99	0.0	0.5	56.0	86.1	98.8	100.0	100.0	100.0
FEB	0.0	0.6	92.1	100.0	100.0	100.0	100.0	100.0
MAR	0.1	5.7	71.2	93.7	99.8	100.0	100.0	100.0
APR	0.1	5.4	50.3	87.4	99.7	100.0	100.0	100.0
MAY	0.2	5.2	29.4	81.0	99.5	100.0	100.0	100.0
JUN	0.0	1.2	8.2	38.6	82.3	97.7	100.0	100.0
JUL	0.0	0.07	1.04	14.3	68.7	96.2	100.0	100.0
AUG	0.0	0.0	0.6	9.7	54.5	91.8	98.7	100.0
SEP	0.0	0.0	0.1	5.0	40.3	87.4	97.4	100.0
OCT	0.0	0.0	0.0	1.2	28.6	61.9	73.6	47.0
NOV 99	0.0	0.1	6.9	28.7	60.0	85.6	89.6	63.0

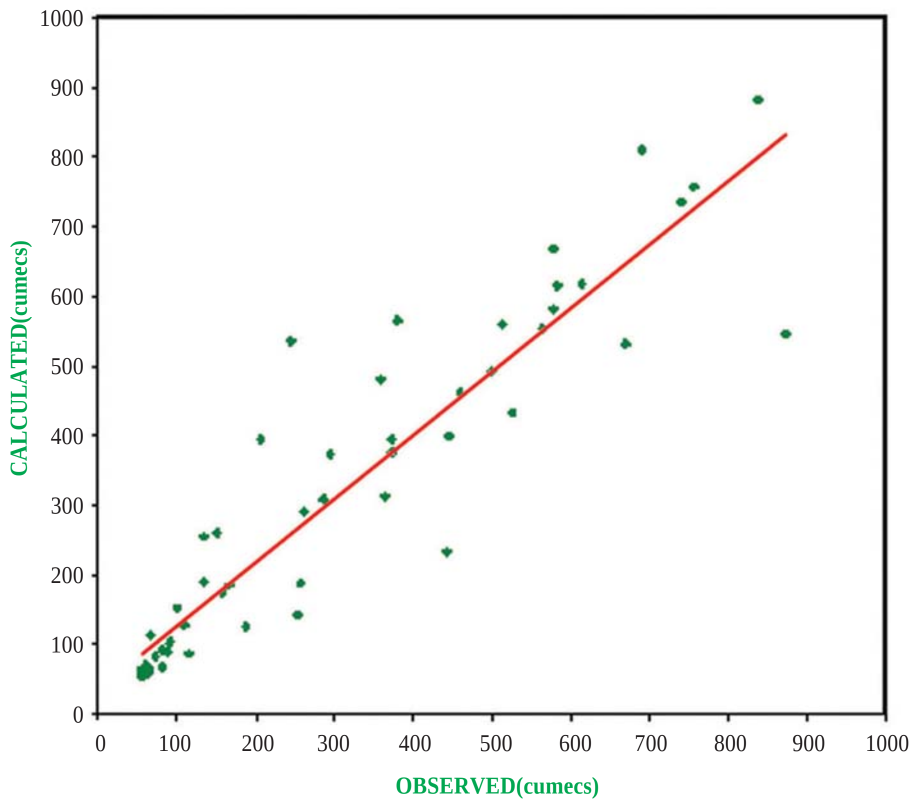

Figure 2 Comparison of Observed and Computed runoff of 10 daily averages at Pandoh Dam.

Table 3 Parameters of SRM model, their units and the temporal frequency

Model Parameter	Symbol	Units	Time Period
Runoff coefficient of Snow	C_S	-	Monthly
Runoff coefficient of Rain	C_R	-	Monthly
Degree day factor	a	cm.°C^{-1}.d^{-1}	Yearly
Critical temperature	T_{CRIT}	°C	Constant
No. Of degree days	**T**	°C.d	10 - Daily
Temperature lapse rate	γ	°C/ 100m	10 - Daily
Snow cover percentage	**S**	%	Monthly
Rainfall	**P**	cm	10 - Daily
Elevation zone area	**A**	Km^2	Constant for each Zone
Récession coefficient	**k**	-	10 - Daily
Previous day's discharge	Q_n	cumecs	10 - Daily
Ten Daily	**n**	day	10 - daily

SRM model calculations: All the parameters derived as explained above are used in the calculations. The list of parameters and their temporal frequency is shown in table 3. The snowmelt calculated for each of the elevation zone using the equation (for description of symbols, refer table 3)

$$Q_{n+1} = [C_{Sn}\, a_n\, (T_n + \Delta T_n)\, S_n + c_{Rn}\, P_n] * A*(10000/86400) * (1-k_{n+1}) + Q_n\, k_{n+1}$$

The snowmelt runoff calculated using the SRM model is compared with the observed data at the Pandoh dam site. The observed and calculated runoff for 10-day averages are plotted and shown in figure 2.

The linear regression relationship between the observed and calculated runoff is

$Q'_1 = 0.9909 * Q_1 + 36.959$

Where

Q^*_1 = Calculated discharge (cumecs)

Q_1 = Observed discharge (cumecs)

The regression coefficient is 0.859. The assessment of model accuracy as given in the SRM model (Martinec et.al, 1998) is coefficient of determination and volume difference, which are calculated using this equation,

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q'_i)^2}{\sum_{i=1}^{n}(Q_i - \bar{Q})^2} \qquad D_v = \frac{V_R - V'_R}{V_R} 100$$

Where,

R^2 = Coefficient of determination

Q_i = Observed 10 daily average discharge

Q'_i = Calculated 10 daily average discharge

$\bar{Q}$ = average daily discharge for the computed year or computed season n = number of ten daily

D_v = percentage difference between the total measured and computed runoff

V_R = measured runoff volume

V'_R = computed runoff volume

Average monthly deviation of computed runoff with observed runoff is + 4.6 %. The coefficient of determination obtained is 0.854. Results of the present study is an improvement over the results of previous study by Kumar, et.al., (1993) in Beas basin in which a computed seasonal snowmelt differ by -5.4 % with observed snowmelt runoff and the coefficient of determination of 0.845.

Acknowledgements

The authors express their since thanks to the Executive Engineer, Bhakra Beas Management Board, Pandoh, Scientist-in-charge, IARI Research station, Katrain and Snow and Avalanche Studies Establishment, Manali who have provided data which has been used in this study.

References

Agrawal, K.C., V. Kumar, and T.Dass, (1983). Snowmelt runoff for a catchment of Beas Basin. *Proceedings of the First National Symposium on Seasonal Snowcover*, 28-30, April, SASE, Manali, Vol-II, pp:43-63.

Dozier, J (1984) Snow reflectance from Landast – 4 Thematic mapper. *IEEE Transactions on Geosciences and Remote Sensing*. 22, pp: 323 - 328.

Griggs, M. (1968) Emissivities of natural surfaces in the 8-to 14-micron spectral region, *J. Geophy. Res*. 73, pp: 7545-51.

Martinec, J. (1975) Snowmelt-Runoff Model for stream flow forecasts. *Nordic Hydrol*. 6(3), pp 145-154.

Martinec, J., A. Rango, and E. Major (1983). *The snowmelt-runoff (SRM) user's manual*. NASA Reference Publ. 1100, NASA, Washington DC, pp:118.

Martinec, J. & Rango, A. (1986) Parameter values for snowmelt runoff modelling. J. *Hydrol*. 84, 197-219.

Martinec, J., Rango, A. & Roberts, R. (1998) *Snowmelt Runoff Model (SRM) User's Manual* (Version 4.0). http://hydrolab.arsusda.gov/cgi-bin/srmhome/srm4.pdf

Ramamoorthi, A.S. (1986). *Snow cover area (SCA) is the main factor in forecasting snowmelt runoff from major river basins*. Large Scale Effects of Seasonal Snow Cover, Proceedings of the Vancouver Symposium, IAHS Publ. No. 166, pp. 187-198.

Rango, A. (1983) Application of simple snowmelt runoff model to large river basins. In: *Proc. Western Snow Conf*. (51 st meeting, Vancouver, Washington, April), pp 89 - 99.

Kumar, V. S., Paul, P.R., Ramana Rao, CH.L.V, Haefner, H. and Siedel, K. (1993) Snowmelt Runoff Forecasting studies in Himalyan Basins. *Snow and Glacier Hydrology*, IAHS publication No. 218. pp 85 - 94.

Singh, P and Quick, M.C. (1993) Streamflow simulation of Satluj River in the Western Himalyas. *Snow and Glacier Hydrology*. IAHS publication no. 218. pp 261 - 271.

Singh,P. and N. Kumar (1996). Determination of snowmelt factor in the Himalayan region. *Hydrological Sciences Journal*, Vol. 41, Pp:301-310.

Singh, P, S.K. Jain, and N. Kumar (1997). Estimation of snow and Glacier contribution to the Chenab River, Western Himalaya. *Mountain Research and Development*, Vol.17, No.1, Pp: 49-56.

Singh, P, H. Huebl and H.W.Weinmeister, (2000). Use of the recession characteristics of snowmelt hydrographs in the assessment of snow water storage in a basin. *Hydrological Process*. 14, Pp: 91-101.

Singh, P, and V.P.Singh (2001). *Snow and Glacier hydrology*. Kluwer Academic Publishers, Dordrecht. pp

World Meteorological Organization (WMO) (1986). *Intercomparison of Models of Snowmelt Runoff*. Operational Hydrol. Report 23, WMO 646, Geneva, Switzerland.